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3-D numerical analysis of EHD turbulent flow and mono-disperse charged particle transport and collection in a wire-plate ESP

Niloofar Farnoosh*, K. Adamiak, G.S.P. Castle

Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario, N6A 5B9 Canada

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ABSTRACT

The present study attempts to develop a detailed numerical approach and a simulation procedure to predict the motion of gas, ions and particles inside a simple parallel plate channel containing a single corona wire. A hybrid Finite Element (FEM)-Flux Corrected Transport (FCT)-Finite Volume (FVM) method is used: the FEM–FCT numerical algorithm is applied for modeling the steady-state corona discharge, while the turbulent gas flow and the particle motion under electrostatic forces are modeled using the commercial CFD code FLUENT. Calculations for the gas flow are carried out by solving the Reynolds-averaged Navier–Stokes equations and turbulence is modeled using the k–ε turbulence model. An additional source term is added to the gas flow equation to include the effect of the electric field, obtained by solving a coupled system of the electric field and charge transport equations using User-Defined Functions (UDFs). The particle phase is simulated based on the Lagrangian approach, where a large number of particles is traced with their motion affected by the gas flow and electrostatic forces using the Discrete Phase Model (DPM) in FLUENT. The developed model is useful to gain insight into the particle collection phenomena that take place inside an ESP.

1. Introduction

Electrostatic precipitation (ESP) has been an important industrial technology since the early 1900s and can be regarded as the major air pollution control device to remove the dust particles from large gas streams. The particle mass collection efficiency of modern industrial wire-plate ESPs is of the order of 99%. However, due to changes in particle emission standards, improving the collection of sub-micron to micron diameter particles is still necessary and is a challenging problem.

Particles and droplets in an ESP are charged by the corona discharge and are driven to the collecting plates by the electric forces. However, the air drag due to gas flow also affects the particle trajectories and the secondary electrohydrodynamic (EHD) flow modifies these trajectories making them even more difficult to predict. Therefore, the complex interactive phenomena between the electric field, turbulent flow field, and particle charging and motion must be taken into account for the full analysis of ESPs.

Since the whole process is rather complicated many efforts have been made to achieve a better understanding of all important phenomena, and many theoretical and numerical investigations have been published during the last several decades. Some authors focused their studies on two-dimensional analysis of electrical conditions only, considering the electrical forces as a primary mechanism affecting the particle trajectories. Various numerical techniques have been used: Finite Element (FEM)-Method of Characteristics (MoC) [1,2], FEM-Boundary Element (BEM)-MoC [3], FEM-Charge Simulation (CSM) [4], FEM-Donor Cell (DCM) [5] and Finite Difference (FDM)-MoC [6]. These methodologies were applied to obtain the electric field and charge density distributions, and V–I characteristics of corona discharge in a 2-D ESP model. In most cases the results were compared with the related experimental data from the literature. However, memory requirements, computation speed and accuracy of the results were quite different for each numerical technique. Moreover, the so-called single species corona model was commonly accepted, where the ionization reactions and ionization layer were neglected and steady flow of a single dominant ion was assumed. While this substantially simplifies calculations, it requires additional information about the amount of generated ions. The most common approaches rely either on the experimental value of the total corona current, or on the semi-empirical Peek's law.

Moving ions in the corona discharge collide with neutral gas molecules causing the gas motion, called secondary electrohydrodynamics (EHD) flow. Various 2-D numerical techniques were used for predicting the EHD flow patterns assuming two

* Corresponding author.
E-mail address: nfarnoos@uwo.ca (N. Farnoosh).

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airflow models: laminar and turbulent. In 2007, Chun et al. [7] obtained 2-D EHD flow pattern for the Chen–Kim k–ε turbulent flow model in a wire-plate ESP using an algorithm they referred to as SIMPLEST, along with CFD software. In 2008, Zhao and Adamiak used a 2-D MoC-FEM–BEM hybrid numerical algorithm along with FLUENT software to generate a complete airflow regime map for different EHD and Reynolds (*Re*) numbers in a wire-plate ESP considering the laminar airflow model [3]. They identified at least eight different flow patterns possible for different external flow and wire voltage levels. Similar studies were also performed to obtain EHD flow patterns in multi-wire ESPs. Kallio and Stock [8] implemented a 2-D FEM-FDM algorithm for modeling a multi-wire ESP to obtain EHD flow patterns assuming the k–ε turbulent flow model. The numerical results were verified experimentally using Laser-Doppler anemometry. In 2002, a 2-D FEM-Finite Volume (FVM) numerical method along with a perturbation analysis of 2-D Euler equations was performed by Schmid et al. for modeling a multi corona wire ESP model [9]. The influence of different flow models: turbulent (k–ε and Reynolds stress-model) and non-turbulent (Euler and laminar) were investigated. A detailed view of important mechanisms leading to formation of the secondary flows was also demonstrated.

Due to deficiencies of two-dimensional approaches in the accurate modeling of a finite length corona wire and three-dimensional characteristics of the EHD flow patterns, some authors tried to develop 3-D computational algorithms for modeling the ESP problems, considering different corona electrode configurations. In 1996 Davidson et al. [10] applied a 3-D FEM-MoC technique to obtain electrical conditions inside an ESP, including current density distribution and electrical fields in point-to-plane and barbed plate-to-plane ESP. A reasonably exact model for computing the charge distribution on the corona electrode surface was assumed and was based on Peek's formula. Although, these numerical results had a good accuracy, the authors never tried to investigate the EHD flow pattern generated in the same configuration.

In [11], Yamamoto et al. used a 3-D FDM numerical technique (SIMPLEST algorithm) for modeling a multi-wire ESP. In their model, point corona electrodes were assumed to take into account the effect of negative corona discharge, which forms so-called tufts. Using a simplistic corona model, 3-D EHD flow and electric patterns (distribution of airflow and electrostatic parameters) were obtained for both turbulent and laminar flow models. They also implemented the same numerical technique for modeling alternatively oriented spike electrodes in a multi-wire industrial ESP configuration to obtain 3-D EHD flow patterns considering the turbulent flow model [12]. An experimental set-up for demonstrating particle trajectories and investigating the effect of particle concentration on the *V*–*I* characteristic curve was previously employed by the same authors to model a full-scale industrial ESP consisting of spiked type wire and convex-concave type collecting plates [13].

Many papers reported in the literature deal with particle trajectory tracing in the ESP. In 2000, Soldati [14] used DNS (Direct Numerical Simulation) to analyze the effects of EHD flow and turbulence on 2-D pre-charged particle transport and collection efficiency in a multi-wire ESP. Using a Lagrangian approach, the particle collection efficiency for particles of different sizes was compared in two cases: with and without EHD flow. According to his investigations, EHD flow has negligible influence on the overall particle collection and on particle deposition at the walls. In [15], Skodras et al. used a Lagrangian approach for calculating the particle concentration and collection efficiency in a multi-wire ESP using 2-D commercial fluid dynamics software considering a turbulent flow model. Effects of particle diameter, inlet velocity and applied voltage on particle collection efficiency were investigated.

In [16], Lei et al. used a 3-D Monte-Carlo method for modeling a multi-wire ESP. Turbulent particle charging and tracing for a range of particle diameters were computed using a Lagrangian approach. As a result, 2-D EHD flow patterns were demonstrated for the turbulent flow model. The variation of different forces acting on particles of different sizes along their trajectories was investigated in detail as well. The authors pointed out that the 3-D numerical simulation is necessary not only to investigate the EHD flow, but also to evaluate different types of forces on the particle's movement.

Laser-Doppler velocimetry (LDV), particle image velocimetry (PIV) systems and hot wire anemometers were used by many authors to experimentally visualize the flow patterns and measure the velocities of the EHD flows [17–19]. Mizeraczyk and his collaborators used 2-D PIV measurements to investigate the effect of various dust concentrations on EHD flow patterns for a laminar flow model in a multi-wire ESP [20]. The results of 3-D PIV measurements of EHD flow patterns in a narrow wire-duct ESP for two wire positions: longitudinal and transverse-to-flow were investigated. The particle collection efficiency for a range of particle diameters, and negative and positive applied voltage in ESP with spike-type electrode were also presented by the same authors in [21,22]. According to their visualizations, the flow patterns in both ESPs (with longitudinal or transverse wire electrode) are very complicated and the particle trajectories in the narrow ESP exhibit a strongly 3D character due to the narrow cross section of the ESP duct. These experimental results also confirmed the very well known fact that decreasing the particle diameter and applied voltage results in decreasing particle collection efficiency.

Because experimental analysis is difficult due to the influence of the electrostatic field on measurements, numerical analysis has been widely preferred. Although, as reported above, various numerical techniques for modeling ESPs have been reported in the literature, none of them could exactly model all phenomena. In this paper, a hybrid method is presented to simulate the 3-D EHD flow produced by the electric corona discharge, particle charging and trajectories and the deposition pattern in a simple wire-duct ESP configuration. This technique is based on FEM to obtain the distributions of the electric field, the electric potential and the space charge density. The airflow distribution, particle trajectories and deposition efficiency have been simulated by a commercial software package FLUENT, which is based on FVM.

This study assumes uniform corona current distribution along the wire, i.e. positive corona discharge, and involves the evaluation of the electrostatic fields, space charge density in the inter-electrode space, the build-up of charge on the particles and resulting electrical forces. In addition, it considers the flow interactions between the primary gas flow and the secondary EHD flow produced by the electric corona discharge. Selected results of the simulation are presented showing the particle trajectories inside the ESP under the influence of both aerodynamic and electrostatic forces.

2. Mathematical model

2.1. Electric field and space charge

Corona discharge takes place in a grounded duct when a high voltage is applied to a central wire having a small radius of curvature. Electric charges injected from the thin ionization layer form a space charge in the drift zone. The electric field is thus governed by Poisson's equation:

$$\begin{aligned}\nabla^2\phi &= -\frac{\rho}{\varepsilon_0}\\ \vec{E} &= -\nabla\phi\end{aligned} \tag{1}$$